Kondo effect with spin selective pseudogap in a double quantum dot ring with Rashba interaction.

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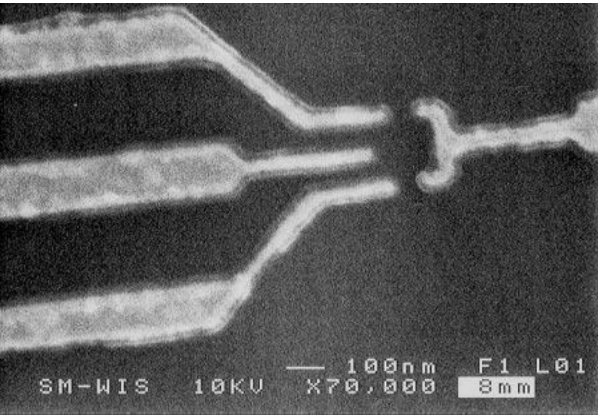
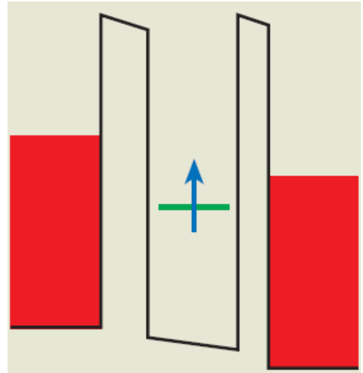
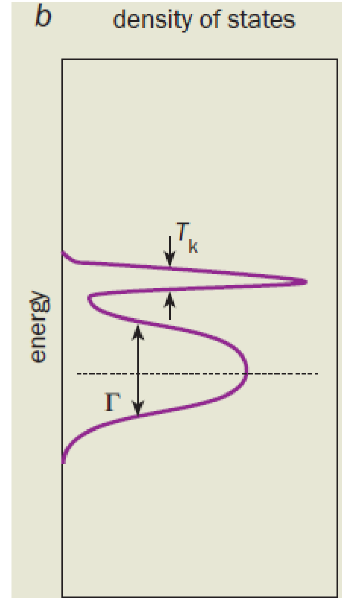
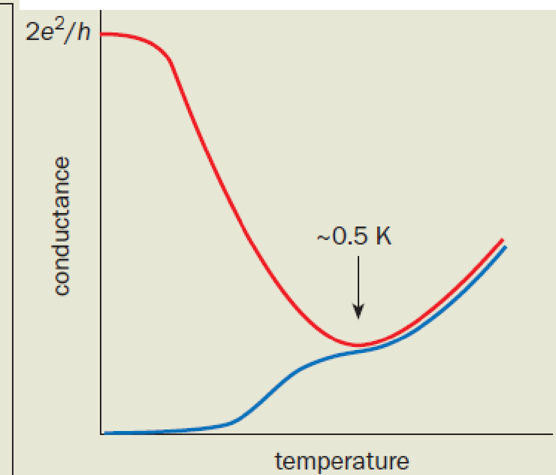
Context of the work:



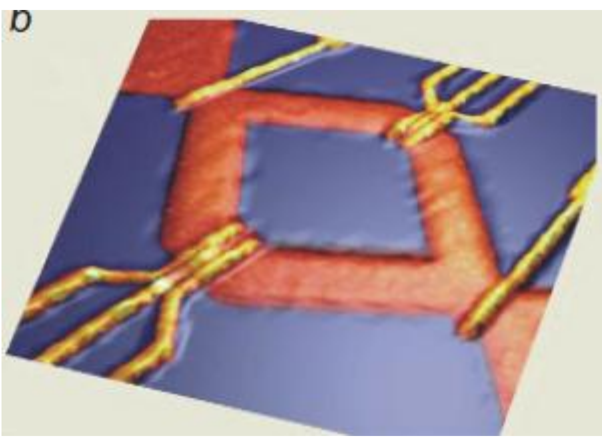
D. Goldhaber-Gordon et al..
Nature’98







Kouwenhoven, Glazman, Physics World’01



Description: Anderson model of a quantum impurity embedded in a host with constant density of states

90-ties: problem of impurity in a complex medium:
a host with pseudogap in its density of states - QPT
„strong coupling regime”$\leftrightarrow$ „local moment regime”

$$\rho^{host}(\epsilon) = C|\epsilon|^r, r = \frac{1}{2}, 1, 2$$

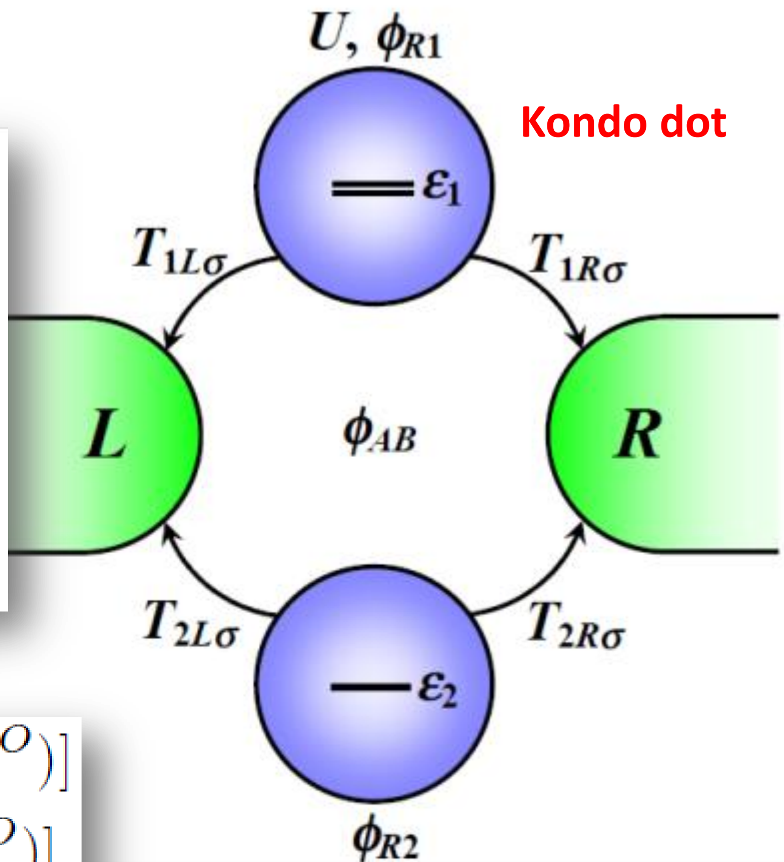
Witthoff, Fradkin, PRL’90

Model: Two quantum dots in A.-B. ring

$$H_{QDs} = \sum_{\gamma=1,2} \sum_{\sigma=\uparrow,\downarrow} [\epsilon_\gamma d^\dagger_{\gamma\sigma} d_{\gamma\sigma} + \frac{1}{2} U n_{1\sigma} n_{1\bar{\sigma}}],$$

$$H_{leads} = \sum_{k,\sigma,\alpha=L,R} \epsilon_{k\alpha} c^\dagger_{k\alpha,\sigma} c_{k\alpha,\sigma},$$

$$H_{tun} = \sum_{\gamma} \sum_{k,\sigma,\alpha} [T_{\gamma\alpha\sigma} c^\dagger_{k\alpha,\sigma} d_{\gamma\sigma} + h.c.].$$



$$T_{1L(R)\sigma} = t_{1L(R)} \exp[\pm(i/2)(\phi_{AB}/2 - \sigma\phi_1^{SO})]$$
$$T_{2L(R)\sigma} = t_{2L(R)} \exp[\mp(i/2)(\phi_{AB}/2 + \sigma\phi_2^{SO})].$$

$\sigma = \pm 1$ for spin $\uparrow,\downarrow$

$$\Gamma_\gamma = 2\pi t_\gamma^2 \rho_0, \;\; \Phi_\sigma = \phi_{AB} - \sigma(\phi_1^{SO} - \phi_2^{SO})$$

$$\phi^{SO}{}_1 - \phi^{SO}{}_2 \equiv \phi^{SO}$$

P.S. J. Phys. Condens. Matter **25** 085303 (2013)

Rashba effect

2D electron gas with strong confinement in y direction:

$$\frac{dV}{dy} \gg \frac{dV}{dx}, \frac{dV}{dz}$$

and $V(y)$ is asymmetric w. r. to $y = 0$

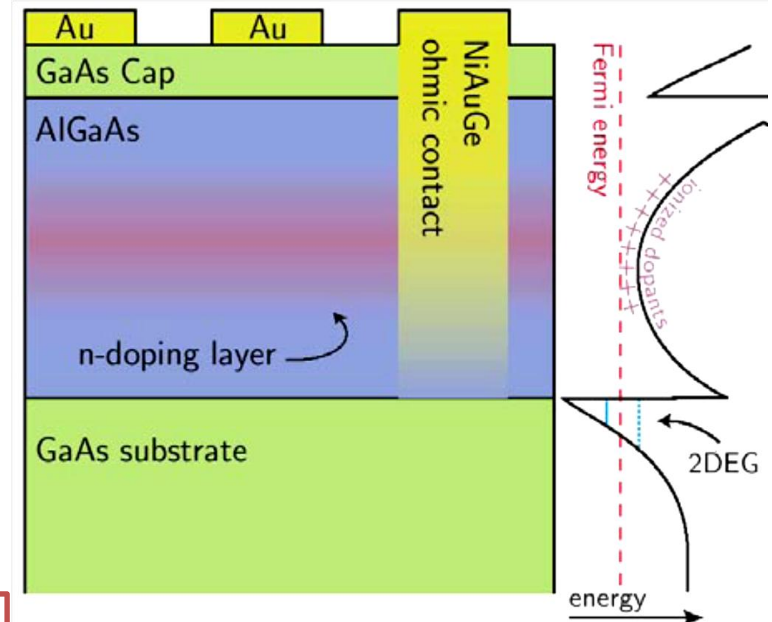
$$H^{Rashba} = \frac{\alpha}{\hbar}(\sigma_z p_x - \sigma_x p_z)$$

$$\boxed{te^{-i\sigma\phi_{SO}} c_{k\sigma} d^{+}{}_{\sigma} + h.c.,} \qquad \boxed{t_{mn} d_{m\uparrow} d^{+}{}_{n\downarrow} + h.c.}$$

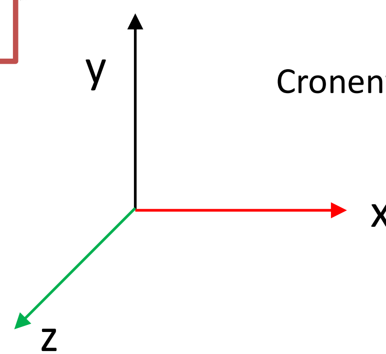
$\sigma = \pm 1$ for spin $\uparrow, \downarrow$

$$\alpha \sim \left\langle \Psi(y) \left| \frac{d}{dy} V(y) \right| \Psi(y) \right\rangle$$

$$\phi_{SO} = k_R \Delta x, \qquad k_R = \frac{\alpha m^*}{\hbar^2}$$

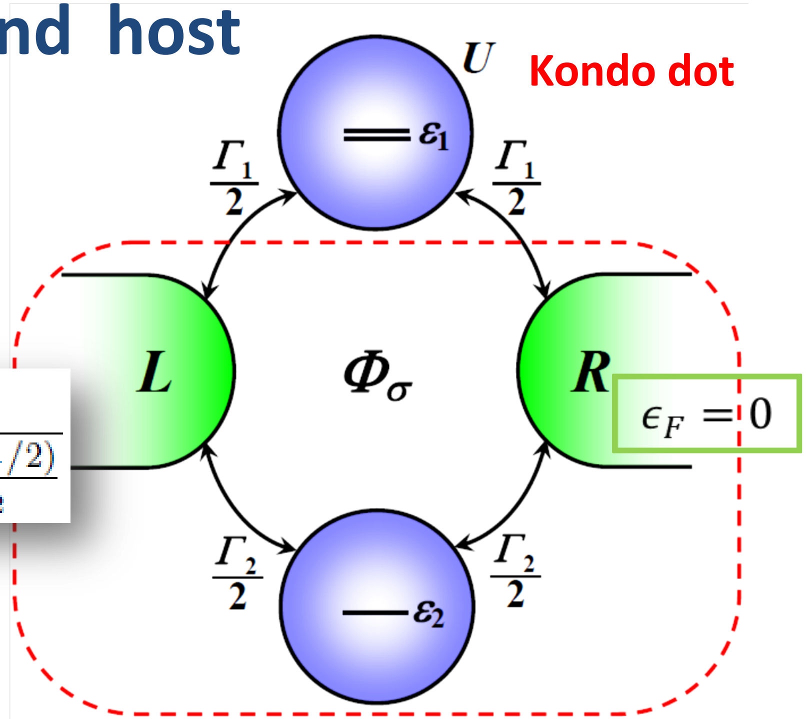


Cronenwett, Thesis 2001



Sun, Wang, Guo, PRB 71, 165310 (2005)

Anderson impurity in a compound host



$\epsilon_2 = \epsilon_F$

Complex host

Properties of the host

Green's function of QD_1 in non-interacting case:

$$G^r_{11,\sigma}(\omega) = \langle\langle d_{1\sigma}; d^\dagger_{1\sigma}\rangle\rangle^r_\omega = \frac{1}{\omega - \epsilon_1 + i\Gamma_1 + \frac{\Gamma_1\Gamma_2\cos^2(\Phi_\sigma/2)}{\omega - \epsilon_2 + i\Gamma_2}}$$

Generalized density of states of the host:

$$\rho^{host}_\sigma(\omega) = \rho_0 \frac{(\omega-\epsilon_2)^2 + \Gamma_2^2 \sin^2\frac{\Phi_\sigma}{2}}{(\omega-\epsilon_2)^2 + \Gamma_2^2}$$

$$\Phi_\sigma = \phi_{AB} - \sigma(\phi_1^{SO} - \phi_2^{SO})$$

Effective splitting:

$$\Delta(\omega) = \epsilon_{1\uparrow} - \epsilon_{1\downarrow} = -\frac{\Gamma_1\Gamma_2(\omega-\epsilon_2)}{(\omega-\epsilon_2)^2+\Gamma_2^2}\sin\phi_{AB}\sin\phi^{SO}$$

Two cases:

1. $\phi_{AB} = \phi^{SO} = 0 \Rightarrow \Phi_\sigma = 0$
   $\rho_\sigma{}^{host}(\epsilon_F) = 0$: pseudo-gap in both σ

2. $\phi_{AB} = \phi^{SO} = \frac{\pi}{2} \Rightarrow \Phi_\uparrow = 0, \Phi_\downarrow = \pi$
   $\rho_\uparrow{}^{host}(\epsilon_F) = 0$, $\rho_\downarrow{}^{host}(\epsilon_F) = \rho_0$:
   pseudo-gap in σ=↑ sector only !

$\epsilon_2 = \epsilon_F \rightarrow \Delta(\epsilon_F) = 0$ always

How about strong electron correlations ?

QD_1 with Coulomb interactions (EOM: Lacroix approximation)

$$G^r_{11\sigma}(\omega) = \frac{1 - \langle n_{\bar\sigma}\rangle - X^r_{\bar\sigma}(\omega)}{\omega - \epsilon_1 + i\Gamma_1 - \Sigma^r_{2\sigma}(\omega)[X^r_{\bar\sigma}(\omega) - 1] - Y^r_{\bar\sigma}(\omega) - i\Gamma_1 X^r_{\bar\sigma}(\omega)}$$

$$X_{\bar\sigma}(\omega) = \sum_{k,\alpha} \frac{T^*_{1\alpha\bar\sigma}}{\omega - \epsilon_{k\alpha}} \langle d^\dagger_{1\bar\sigma} c_{k\alpha\bar\sigma}\rangle, \quad Y_{\bar\sigma}(\omega) = \sum_{k,k',\alpha} \frac{|T_{1\alpha\bar\sigma}|^2}{\omega - \epsilon_{k\alpha}} \langle c^\dagger_{k'\alpha\bar\sigma} c_{k\alpha\bar\sigma}\rangle$$

$$X^r_{\bar\sigma}(\omega) = -\frac{1}{\pi}\left[\Gamma_1 + i\Sigma^a_{2\bar\sigma}(\omega)\right] G^a_{11\bar\sigma}(\omega) \int_{-D}^{+D} d\omega' \frac{f(\omega')}{\omega' - \omega - i\delta},$$

$$Y^r(\omega) = -\frac{\Gamma_1}{\pi} \int_{-D}^{+D} d\omega' \frac{f(\omega')}{\omega' - \omega - i\delta}.$$

$$\Sigma^r_{2\sigma}(\omega) = \frac{\Gamma_1\Gamma_2 \cos^2\frac{\Phi_\sigma}{2}}{\omega - \epsilon_2 + i\Gamma_2}$$

$$\langle n_\sigma\rangle = -\frac{1}{\pi}\int_{-\infty}^{+\infty} d\omega\, f(\omega)\Im G^r_{11,\sigma}(\omega)$$

$$\int_{-D}^{D} d\omega' \frac{f(\omega')}{\omega' - (\omega \pm i\delta)} = \Psi\left(\frac{1}{2} \mp \frac{i\beta\omega}{2\pi}\right) - \ln\left(\frac{\beta D}{2\pi}\right) \pm i\frac{\pi}{2}$$

C. Lacroix, J. Phys. F: Met. Phys. 11, 2389 (1981)

V. Kashcheyevs, A. Aharony, O. Entin-Wohlman, PRB 73, 125338 (2006)

$$\beta = \frac{1}{T}$$

Electron correlations at Fermi level for different effective phases Φ_σ

$$X_{\bar\sigma}(\omega)=\sum_{k,\alpha}\frac{T^*_{1\alpha\bar\sigma}}{\omega-\epsilon_{k\alpha}}\langle d^\dagger_{1\bar\sigma}c_{k\alpha\bar\sigma}\rangle,\quad Y_{\bar\sigma}(\omega)=\sum_{k,k',\alpha}\frac{|T_{1\alpha\bar\sigma}|^2}{\omega-\epsilon_{k\alpha}}\langle c^\dagger_{k'\alpha\bar\sigma}c_{k\alpha\bar\sigma}\rangle$$

$\epsilon_2=\epsilon_F$

1. $\boldsymbol{\phi_{AB}=\phi^{SO}=0\Rightarrow\Phi_\sigma=0}$

$\rho_\sigma{}^{host}(\epsilon_F)=0$: pseudo-gap in both σ

QD_1- leads: $\tilde X_\sigma(\epsilon_F)=0$

leads: $\tilde Y(\epsilon_F)-$ finite

$$G^r_{11,\sigma}(\epsilon_F)=\frac{1-\langle n_{\bar\sigma}\rangle}{\epsilon_F-\epsilon_1-Y^r(\epsilon_F)}$$

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2. $\boldsymbol{\phi_{AB}=\phi^{SO}=\frac{\pi}{2}\Rightarrow\Phi_\uparrow=0,\Phi_\downarrow=\pi}$

$\rho_\uparrow{}^{host}(\epsilon_F)=0$, $\rho_\downarrow{}^{host}(\epsilon_F)=\rho_0$:

pseudo-gap in σ=↑ sector only

QD_1- leads: $\tilde X_\uparrow(\epsilon_F)=0$,

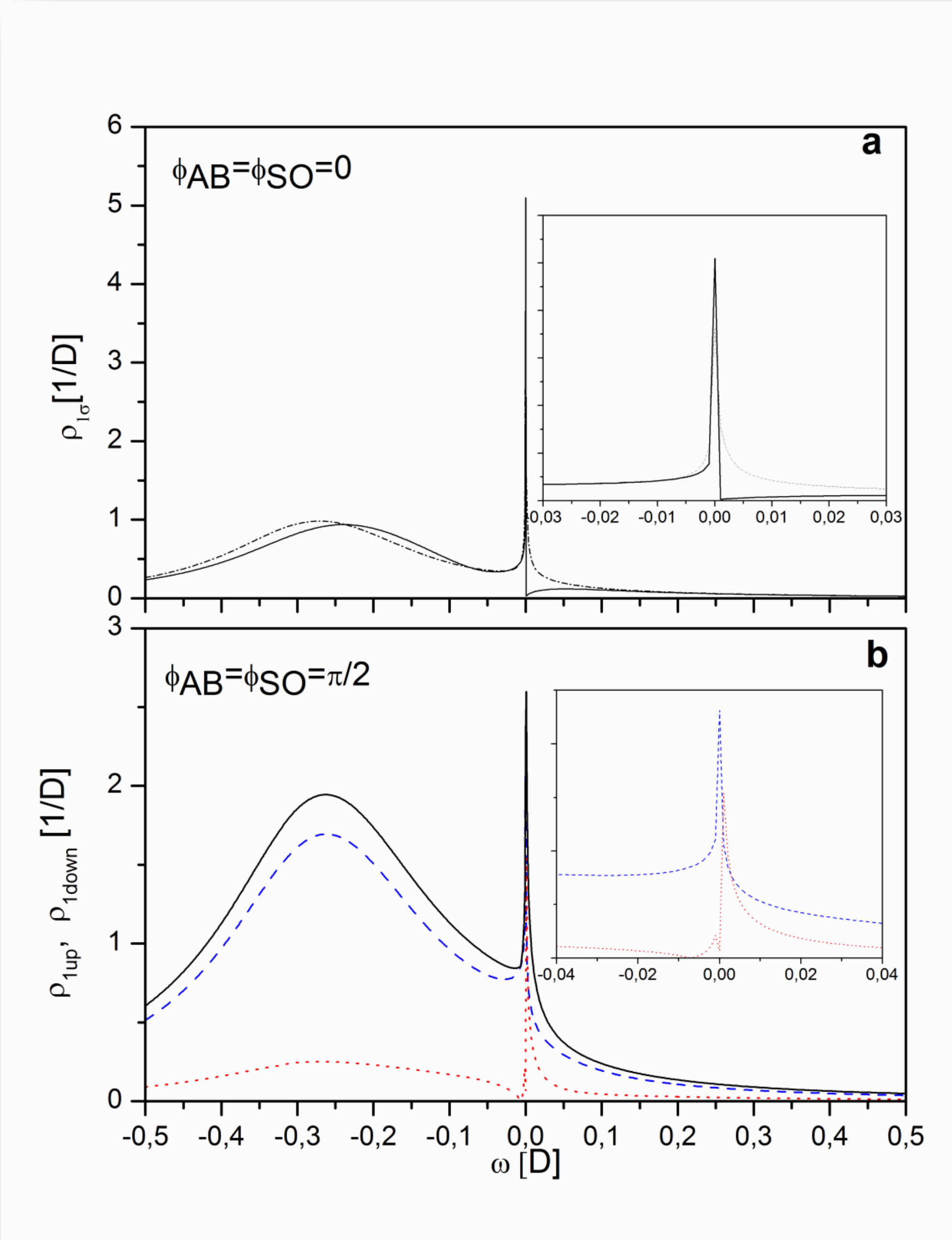
$\tilde X_\downarrow(\epsilon_F)=G_{11,\downarrow}{}^a(\epsilon_F)\tilde Y(\epsilon_F)$

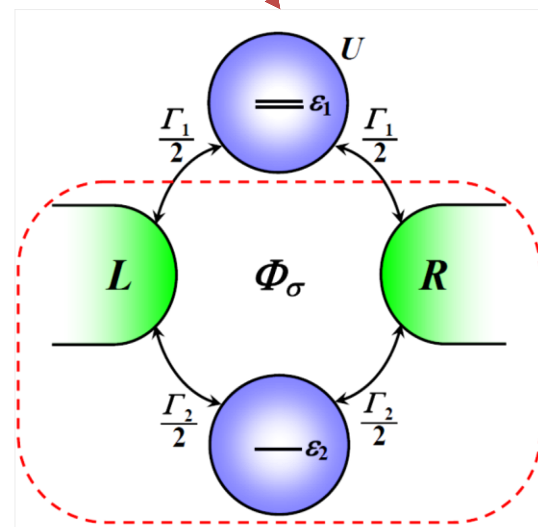
leads: $\tilde Y(\epsilon_F)-$ finite

$$G^r_{11,\downarrow}(\epsilon_F)=\frac{1-\langle n_\uparrow\rangle}{\epsilon_F-\epsilon_1+i\Gamma_1-\tilde Y^r(\epsilon_F)},$$

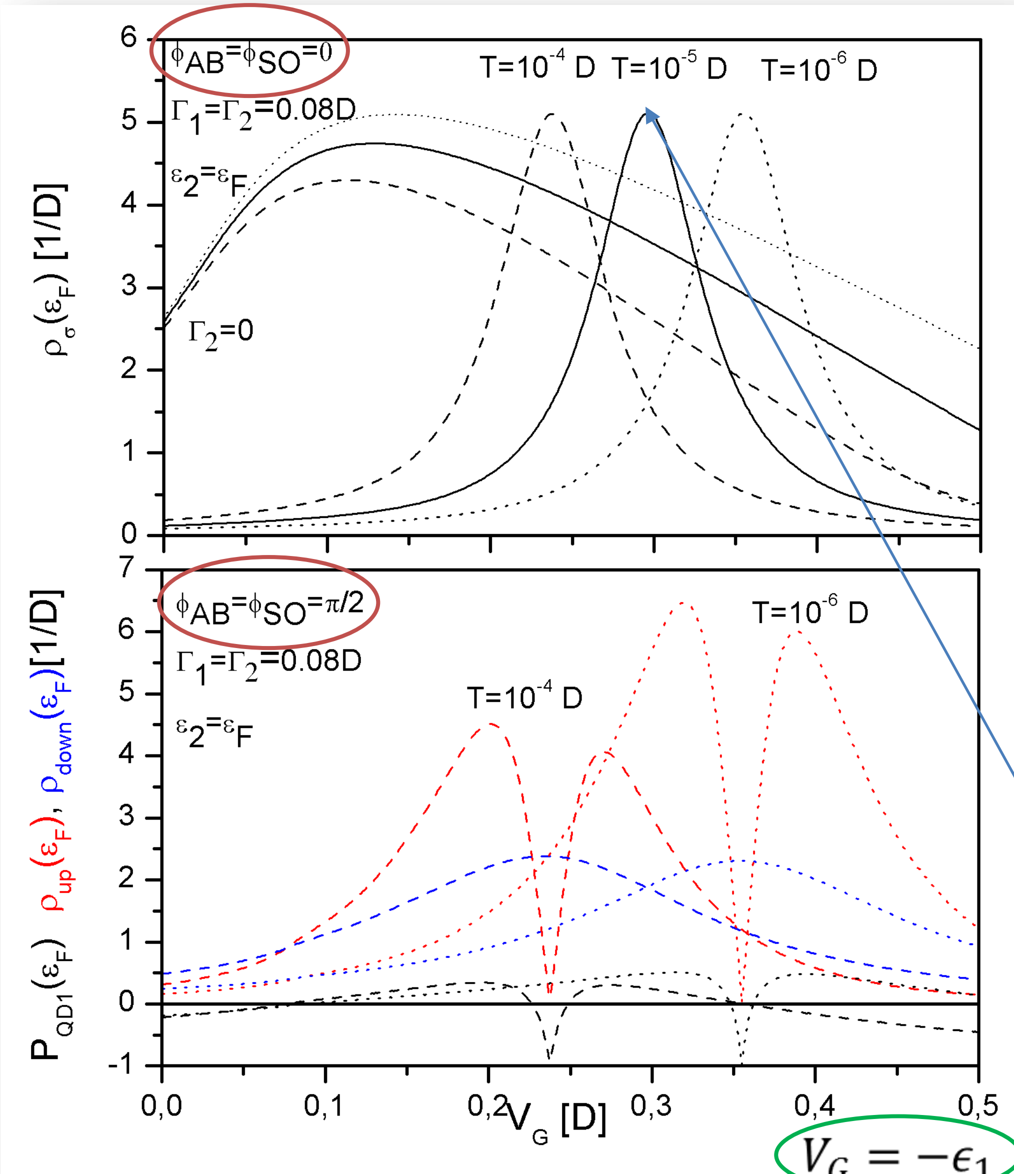
$$G^r_{11,\uparrow}(\epsilon_F)=\frac{1-\langle n_\downarrow\rangle-G^a_\downarrow(\epsilon_F)\tilde Y^r(\epsilon_F)}{\epsilon_F-\epsilon_1-\tilde Y^r(\epsilon_F)}.$$

Spectral densities of the Kondo dot





How does the system behave on Fermi level ?



$$\rho_\sigma(\omega) = -\frac{1}{\pi} Im\, G_{11\sigma}(\omega)$$

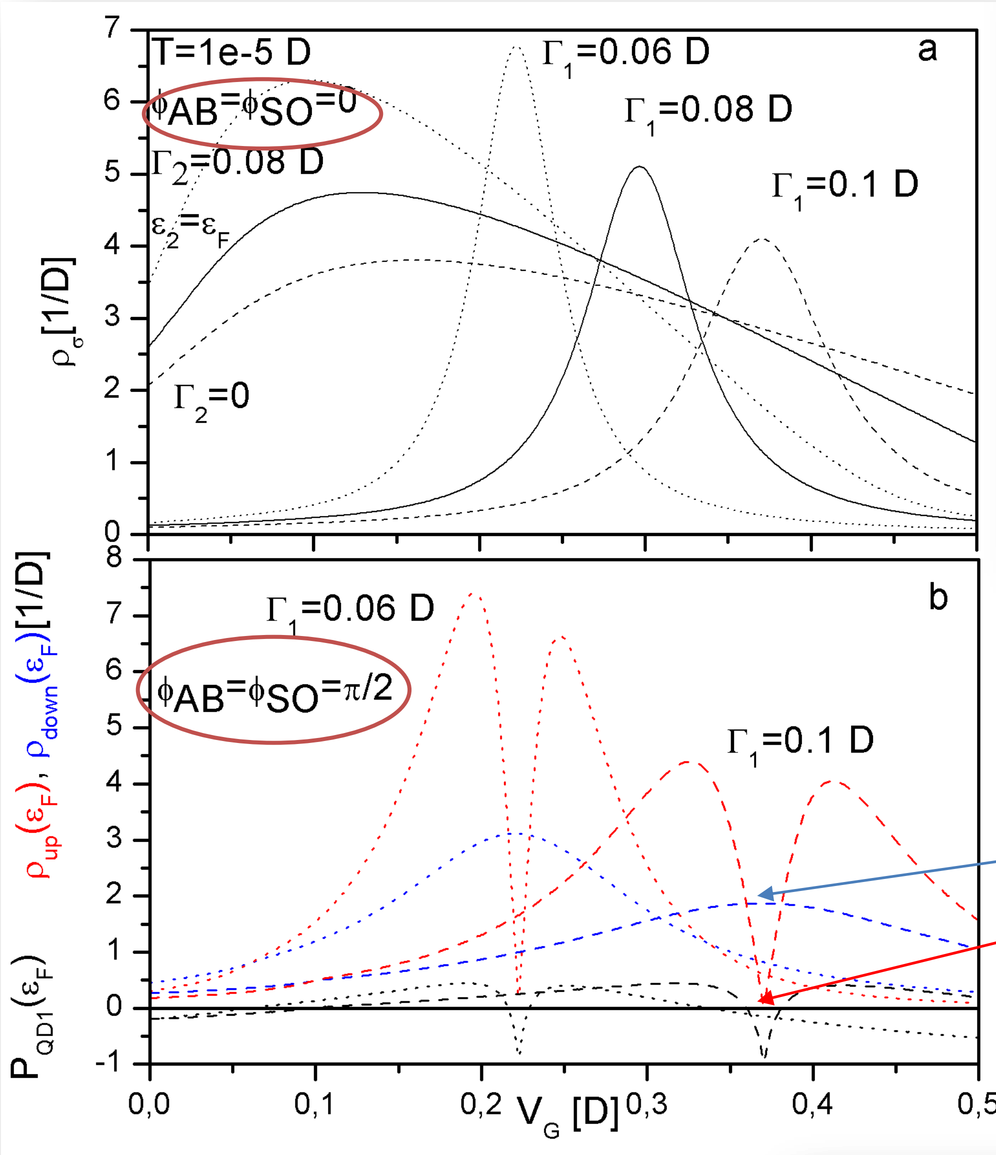
the special value of $\varepsilon_1 = \varepsilon_1^*$
when $\varrho_\sigma(\varepsilon_F) = \varrho_\sigma{}^{max}$ for $\Phi_\sigma = 0$

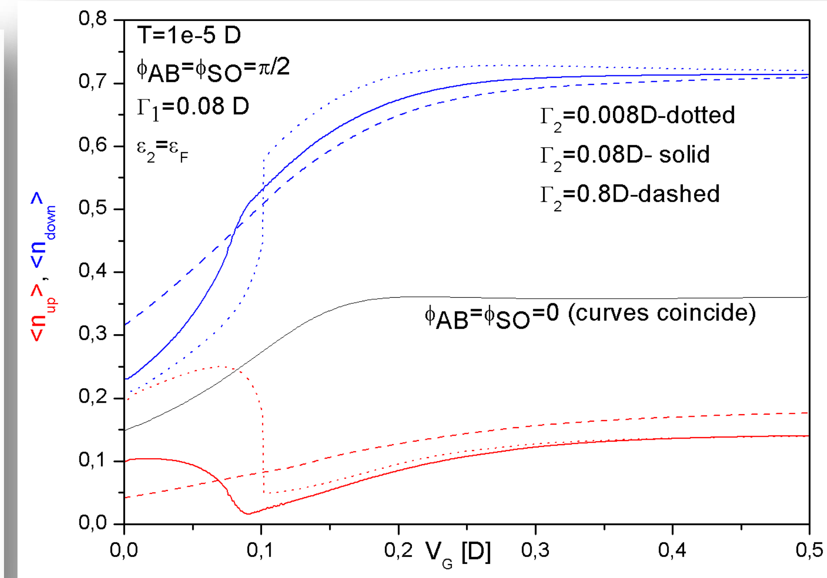
$$\epsilon_1^* = -\frac{\Gamma_1}{\pi}[\Psi(\frac{1}{2}) - \ln(\frac{\beta D}{2\pi})] \qquad \beta = \frac{1}{T}$$

$$T^* = \frac{2}{\pi} D e^{\gamma} \exp(\frac{-\pi|\epsilon_1|}{\Gamma_1})$$

it corresponds to Kondo temperature in Lacroix approximation

$$\rho_{1\sigma}^{max}(\epsilon_F, \epsilon_1^*) = (\frac{2}{\pi})\frac{1-\langle n_{\bar\sigma}\rangle}{\Gamma_1}$$





$$V_G = -\epsilon_1$$

$$\rho_{1\downarrow}^{max}(\epsilon_F,\epsilon_1^*) = \left(\frac{2}{\pi}\right)\frac{1-\langle n_\uparrow\rangle}{3\Gamma_1},$$

$$\rho_{1\uparrow}^{min}(\epsilon_F,\epsilon_1^*) = \left(\frac{2}{\pi}\right)\frac{1-\langle n_\downarrow\rangle}{\Gamma_1} - \rho_{1\downarrow}^{max}(\epsilon_F,\epsilon_1^*).$$

$$P_{QD_1}(\epsilon_F) = \frac{\rho_{1\uparrow}^{min}(\epsilon_F)-\rho_{1\downarrow}^{max}(\epsilon_F)}{\rho_{1\uparrow}^{min}(\epsilon_F)+\rho_{1\downarrow}^{max}(\epsilon_F)} = 1-\left(\frac{2}{3}\right)\frac{1-\langle n_\uparrow\rangle}{1-\langle n_\downarrow\rangle}$$

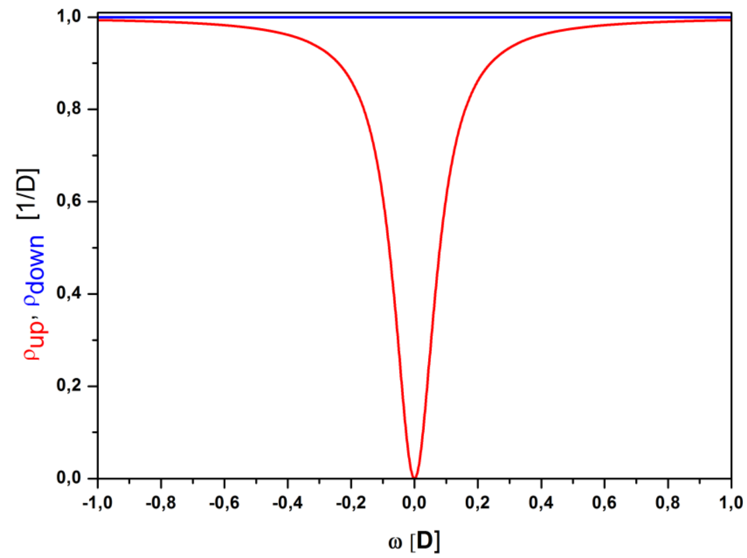
Experimental aspect:

Spin polarization on Fermi level arises as a result of opening a pseudogap in one spin sector only. It is realized when the absolute values of A.-B. and Rashba phases $|\phi_{AB}| = |\phi_{SO}|$. The polarization has oscilatory dependence on magnetic field and not linear as it would be for Zeeman field.

$$\rho_\sigma^{host}(\omega) = \rho_0 \frac{(\omega - \epsilon_2)^2 + \Gamma_2^2 \sin^2 \frac{\Phi_\sigma}{2}}{(\omega - \epsilon_2)^2 + \Gamma_2^2}$$

dla $\epsilon_2 = \epsilon_F$,

$$\rho_\sigma^{host}(\epsilon_F) = \begin{cases} \rho_0 \sin^2 \dfrac{\phi_{AB} - \phi_{SO}}{2}, \sigma = \uparrow \\ \rho_0 \sin^2 \dfrac{\phi_{AB} + \phi_{SO}}{2}, \sigma = \downarrow \end{cases}$$



How the existence of spin dependent pseudogap manifests in electron transport ?

Electron transport through the device

$$J_\sigma = \frac{ie}{2h}\int_{-\infty}^{+\infty} d\epsilon Tr\{[\hat{\Gamma}^L_\sigma(\epsilon)f_L(\epsilon)-\hat{\Gamma}^R_\sigma(\epsilon)f_R(\epsilon)][\hat{G}^r_\sigma(\epsilon)-\hat{G}^a_\sigma(\epsilon)]+[\hat{\Gamma}^L_\sigma(\epsilon)-\hat{\Gamma}^R_\sigma(\epsilon)]\hat{G}^<_\sigma(\epsilon)\}$$

$$\begin{aligned}
G^r_{22,\sigma}(\omega) &= \frac{1}{\omega-\epsilon_2+i\Gamma_2+\Gamma_1\Gamma_2\cos^2(\Phi_\sigma/2)G^{0r}_{11}(\omega)},\\
G^r_{12,\sigma}(\omega) &= \frac{-i\sqrt{\Gamma_1\Gamma_2}\cos(\Phi_\sigma/2)}{\omega-\epsilon_2+i\Gamma_2}G^r_{11,\sigma}(\omega) = -i\sqrt{\Gamma_1\Gamma_2}\cos(\Phi_\sigma/2)G^{0r}_{22}(\omega)G^r_{11,\sigma}(\omega),\\
G^r_{21,\sigma}(\omega) &= -i\sqrt{\Gamma_1\Gamma_2}\cos(\Phi_\sigma/2)G^r_{22,\sigma}(\omega)G^{0r}_{11,\sigma}(\omega).
\end{aligned}$$

$$\hat{\Gamma}^L_\sigma = \begin{bmatrix} \Gamma_1 & \sqrt{\Gamma_1\Gamma_2}\exp(i\frac{\Phi_\sigma}{2}) \\ \sqrt{\Gamma_1\Gamma_2}\exp(-i\frac{\Phi_\sigma}{2}) & \Gamma_2 \end{bmatrix} = (\hat{\Gamma}^R_\sigma)^\star.$$

$$\hat{G}^< = \hat{G}^r\hat{\Sigma}^<\hat{G}^a$$

$$\hat{\Sigma}^<_\sigma = \begin{bmatrix} i\Gamma_1[f_L(\epsilon)+f_R(\epsilon)] & i\sqrt{\Gamma_1\Gamma_2}[f_L(\epsilon)\exp(-i\frac{\Phi_\sigma}{2})+f_R(\epsilon)\exp(i\frac{\Phi_\sigma}{2})] \\ i\sqrt{\Gamma_1\Gamma_2}[f_L(\epsilon)\exp(i\frac{\Phi_\sigma}{2})+f_R(\epsilon)\exp(-i\frac{\Phi_\sigma}{2})] & i\Gamma_2[f_L(\epsilon)+f_R(\epsilon)] \end{bmatrix}$$

Y. Meir, N.S. Wingreen, Phys. Rev. Lett., 68, 2512 (1992)

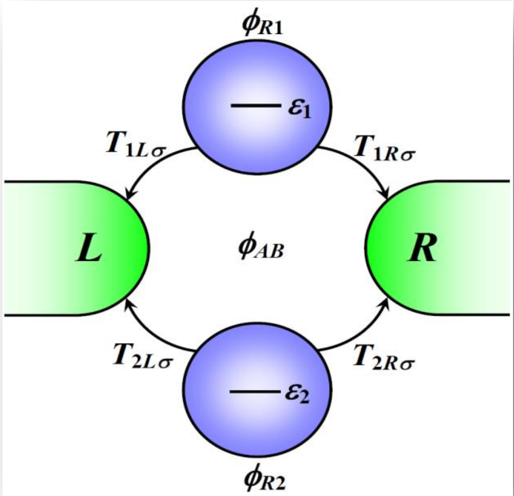
Conductance in the limit of zero bias

$$\mathcal{G}_\sigma \equiv \frac{\partial J_\sigma}{\partial V}\bigg|_{V\to 0}$$

$$\begin{aligned}
\mathcal{G}_\sigma &= \frac{e^2}{h}\int_{-\infty}^{+\infty} d\epsilon \left(-\frac{\partial f(\epsilon)}{\partial \epsilon}\right) T_\sigma(\epsilon),\\
T_\sigma(\epsilon) &= -\Gamma_1 \Im G_{11,\sigma}(\epsilon) - \Gamma_2 \Im G_{22,\sigma}(\epsilon)\\
&+\Gamma_1\Gamma_2\cos^2\left(\frac{\Phi_\sigma}{2}\right)[\Re G_{22,\sigma}(\epsilon)\Re G_{11}^0(\epsilon) + \Re G_{22}^0(\epsilon)\Re G_{11,\sigma}(\epsilon) +\\
&\quad -\Im G_{22,\sigma}(\epsilon)\Im G_{11}^0(\epsilon) - \Im G_{22}^0(\epsilon)\Im G_{11,\sigma}(\epsilon)] +\\
&\quad -2\Gamma_1\Gamma_2\sin^2\left(\frac{\Phi_\sigma}{2}\right)[\Re G_{11,\sigma}(\epsilon)\Re G_{22,\sigma}(\epsilon) + \Im G_{11,\sigma}(\epsilon)\Im G_{22,\sigma}(\epsilon)]
\end{aligned}$$

$$G^0{}_{jj}(\epsilon) = [\epsilon - \epsilon_j + i\Gamma_j]^{-1}, j = 1, 2$$

Noninteracting case, T=0: emergence of dark states

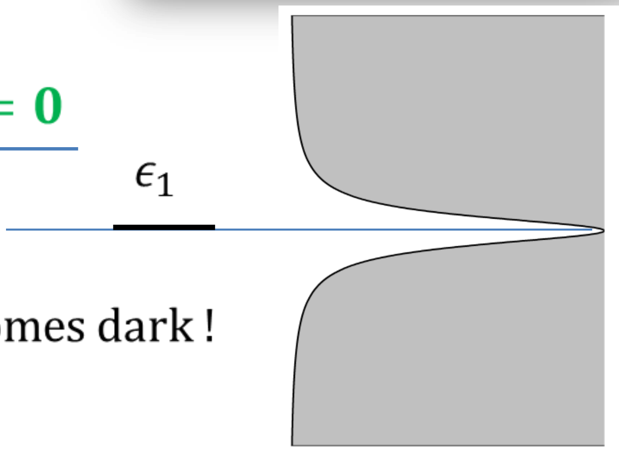


$$-(\partial f(\epsilon)/\partial\epsilon) \rightarrow \delta(\epsilon_F) \qquad \mathcal{G}_\sigma = (e^2/h)T_\sigma(\epsilon_F)$$

$$G^{non,r}_{jj\sigma}(\omega) = \frac{1}{\omega - \epsilon_j + i\Gamma_j + \frac{\Gamma_j\Gamma_k\cos^2(\Phi_\sigma/2)}{\omega-\epsilon_k+i\Gamma_k}}, \quad j,k = 1,2.$$

$\epsilon_{2\sigma} = \epsilon_F$

1. Pseudogap in the both spin sectors: $\Phi_\sigma = 0$



$\omega = \epsilon_F$: $G_{11,\sigma}(\epsilon_F) = \frac{1}{\epsilon_F - \epsilon_{1\sigma}}$: dark state !

if additionally $\epsilon_{1\sigma} \rightarrow \epsilon_F$: $G_{22,\sigma}(\epsilon_F) = \frac{1}{\epsilon_F - \epsilon_{2\sigma}}$, ϵ_2 also becomes dark !

$T_\sigma(\epsilon_F) = 0$ transport is totally blocked !

if $\epsilon_{1\sigma} \neq \epsilon_F$ $T_\sigma(\epsilon_F) = 1$

In finite temperature: when $\epsilon_{1\sigma} = \epsilon_{2\sigma} = \epsilon_F$, always $\mathcal{G}_\sigma = 1$

2. Pseudogap only in spin up sector: $\Phi_\uparrow = 0$ and $\Phi_\downarrow = \pi$

for spin ↑:

$$\omega = \epsilon_F, \epsilon_{2\uparrow} = \epsilon_F, \qquad G_{11,\uparrow}(\epsilon_F) = \frac{1}{\epsilon_F - \epsilon_{1\uparrow}} : \text{dark state}$$

when additionally $\epsilon_{1\uparrow} \to \epsilon_F$: $G_{22,\uparrow} = \frac{1}{\epsilon_F - \epsilon_{2\uparrow}}$, ϵ_2 is also dark state

$T_\uparrow(\epsilon_F) = 0$ transport totally blocked

$T_\uparrow(\epsilon_F) = 1$ when $\epsilon_1 \neq \epsilon_F$ (or finite temperature)

for spin ↓ :

$$G^{non,r}_{jj\sigma}(\omega) = \frac{1}{\omega - \epsilon_j + i\Gamma_j + \cancel{\frac{\Gamma_j\Gamma_k \cos^2(\Phi_\sigma/2)}{\omega - \epsilon_k + i\Gamma_k}}}$$

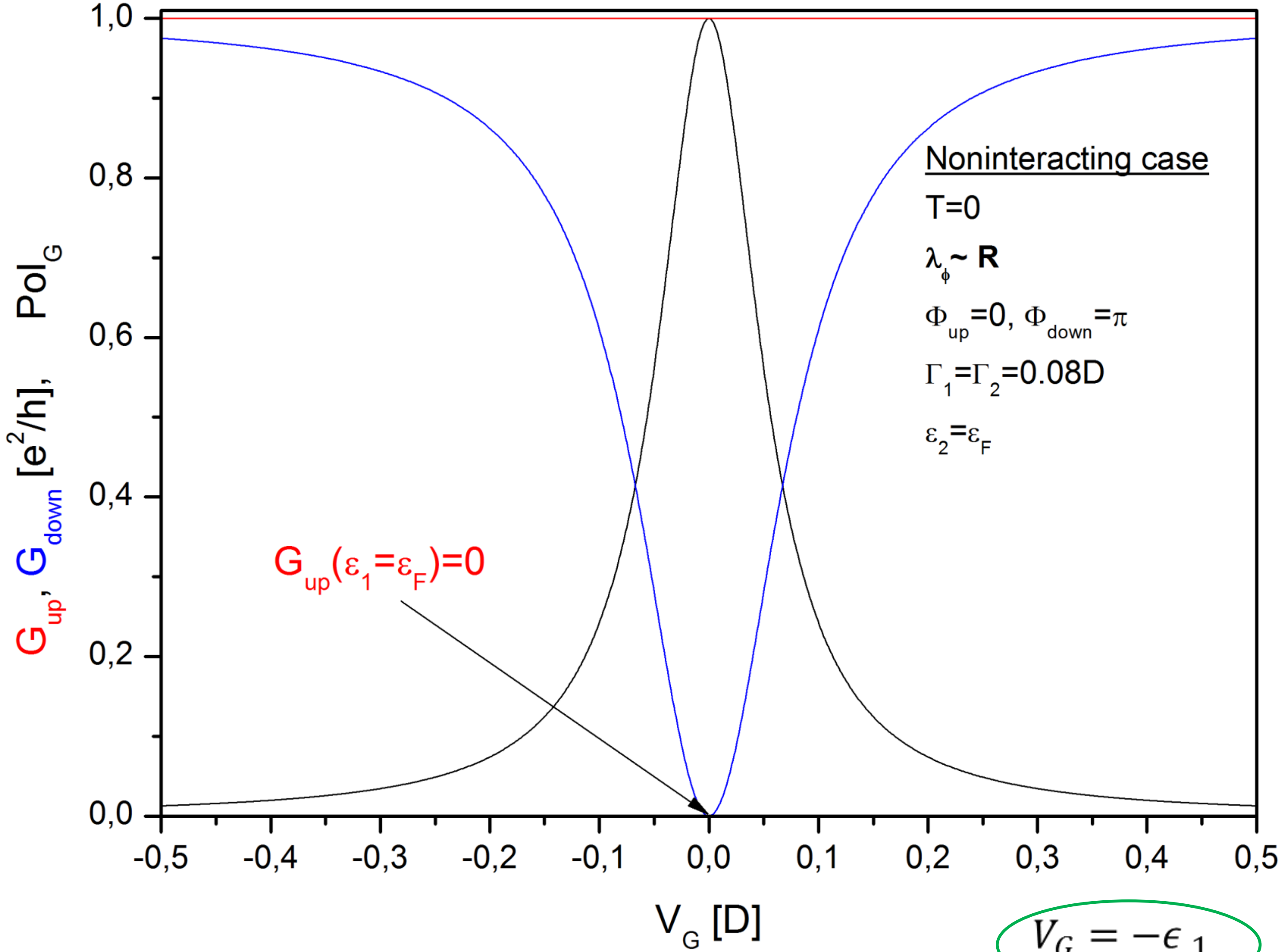
$$G_{jj,\downarrow}(\epsilon_F) = \frac{1}{\epsilon_F - \epsilon_{j\downarrow} + i\Gamma_j},$$

$$T_\downarrow(\epsilon_F) = \frac{(\Gamma_1\epsilon_{2\downarrow} - \Gamma_2\epsilon_{1\downarrow})^2}{({\epsilon_{1\downarrow}}^2 + {\Gamma_1}^2)({\epsilon_{2\downarrow}}^2 + {\Gamma_2}^2)} = \frac{{\Gamma_2}^2}{{\epsilon_{2\downarrow}}^2 + {\Gamma_2}^2}\boxed{\frac{(\tilde{\epsilon}_{1\downarrow} + q)^2}{{\tilde{\epsilon}_{1\downarrow}}^2 + 1}}, \tilde{\epsilon}_{1\downarrow} = \frac{\epsilon_F - \epsilon_{1\downarrow}}{\Gamma_1}, q = -\frac{\epsilon_F - \epsilon_{2\downarrow}}{\Gamma_2}$$

Fano formula (1960)

when $\epsilon_{1\downarrow}, \epsilon_{2\downarrow} \to \epsilon_F$: $T_\downarrow(\epsilon_F) = 0$ destructive quantum interference

when $\epsilon_{2\downarrow} = \epsilon_F$ but $\epsilon_{1\downarrow} \neq \epsilon_F$ $\quad T_\downarrow(\epsilon_F) = \frac{{\tilde{\epsilon}_{1\downarrow}}^2}{{\tilde{\epsilon}_{1\downarrow}}^2 + 1}$

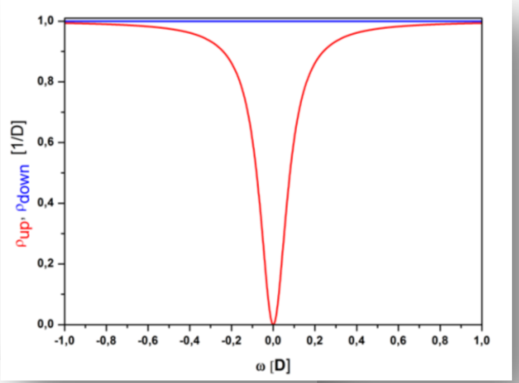


Noninteracting case
T=0
λ_φ~ R
Φ_up=0, Φ_down=π
Γ_1=Γ_2=0.08D
ε_2=ε_F
G_up(ε_1=ε_F)=0
G_up, G_down [e^2/h], Pol_G
V_G [D]
1,0
0,8
0,6
0,4
0,2
0,0
-0,5
-0,4
-0,3
-0,2
-0,1
0,0
0,1
0,2
0,3
0,4
0,5

$V_G = -\epsilon_1$

Interacting case with Kondo dot in the upper A.-B. arm (T finite)

Pseudogap in spin up sector only: $\boldsymbol{\Phi_\uparrow = 0}$ and $\boldsymbol{\Phi_\downarrow = \pi}$



$$G^r_{11\sigma}(\omega) = \frac{1 - \langle n_{\bar\sigma}\rangle - X^r_{\bar\sigma}(\omega)}{\omega - \epsilon_1 + i\Gamma_1 - \Sigma^r_{2\sigma}(\omega)[X^r_{\bar\sigma}(\omega) - 1] - Y^r_{\bar\sigma}(\omega) - i\Gamma_1 X^r_{\bar\sigma}(\omega)}$$

for spin $\uparrow$:

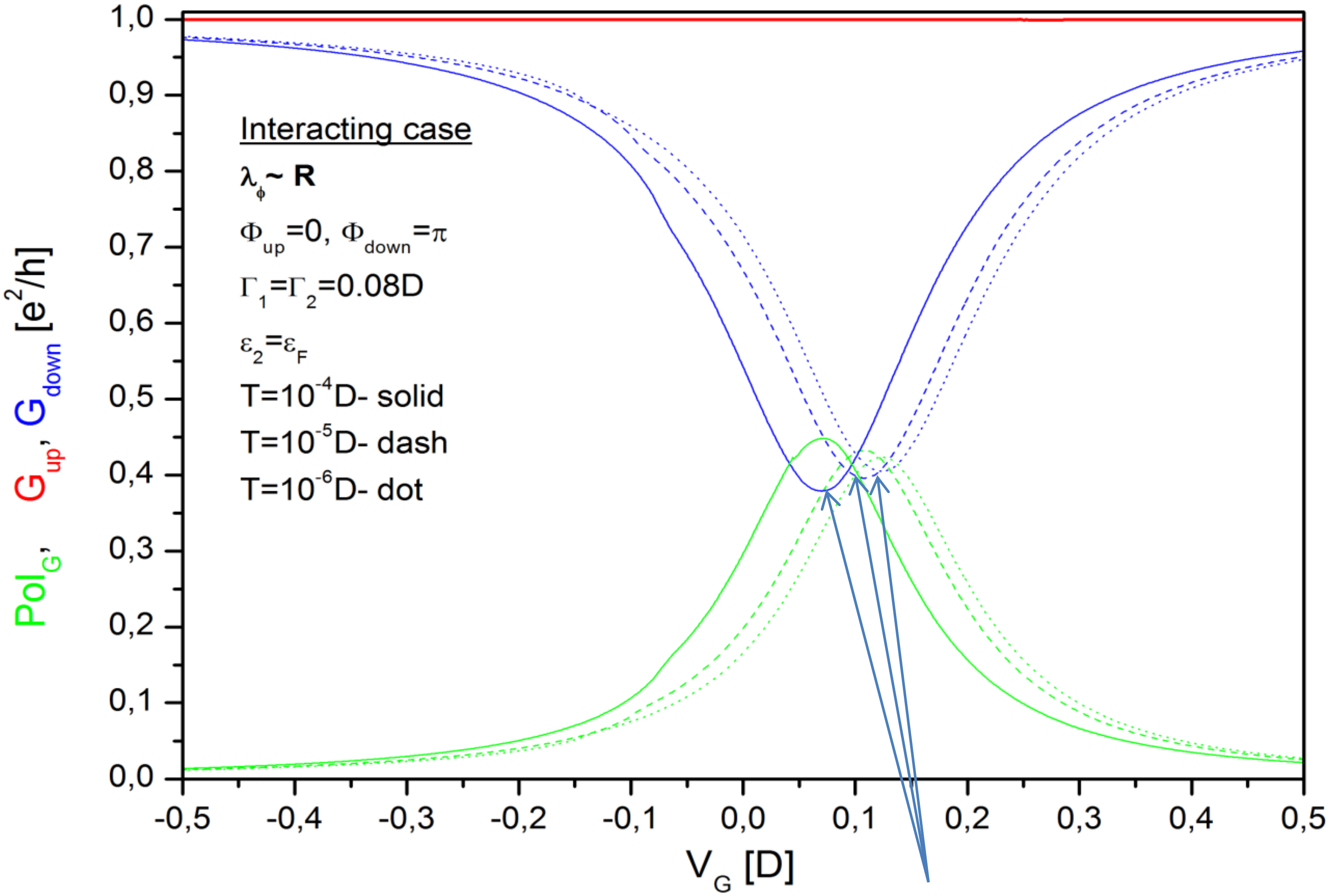
1. correlations QD_1 – leads $X_\downarrow(\omega)$ are retained
2. pseudogap in spin up sector is smeared by thermal fluctuations

$$G^r_{11,\uparrow}(\epsilon_F) = \frac{1 - \langle n_\downarrow\rangle - G^a_\downarrow(\epsilon_F)\tilde{Y}^r(\epsilon_F)}{\epsilon_F - \epsilon_1 - \tilde{Y}^r(\epsilon_F)}$$

for spin $\downarrow$:

1. correlations QD – leads $X_\uparrow(\epsilon_F) = 0$ and are diminished by pseudogap
2. indirect coupling to ϵ_2 excluded

$$G^r_{11,\downarrow}(\epsilon_F) = \frac{1 - \langle n_\uparrow\rangle}{\epsilon_F - \epsilon_1 + i\Gamma_1 - \tilde{Y}^r(\epsilon_F)}$$



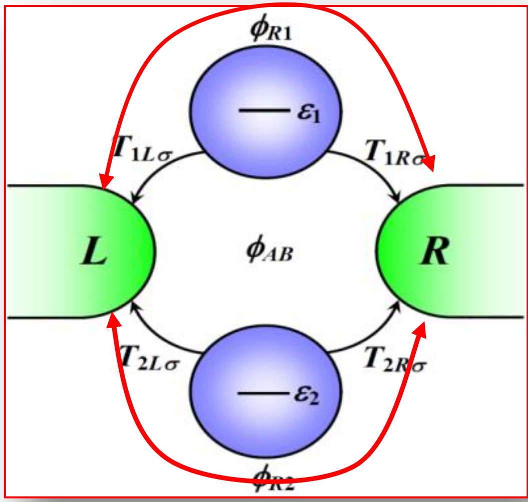
$$V_G = -\epsilon_1{}^*$$

$$T_\downarrow(\epsilon_F, \epsilon_1^\star) = \left[1 - \frac{2}{3}(1 - \langle n_\uparrow \rangle)\right]$$

$$\epsilon_1^* = -\frac{\Gamma_1}{\pi}[\Psi(\frac{1}{2}) - \ln(\frac{\beta D}{2\pi})] \qquad \beta = \frac{1}{T}$$

The minimum deepens with *increase* of temperature !

How these results will be modified when the phase coherence length is smaller than the circumference of the ring , $l_\phi < R$?



Example:

Interacting quantum dots act as dymanical scatterers. Shortening of l_ϕ by Coulomb interactions has been experimentally proven in GaAs/AlGaAs heterostructure [Yacoby et.al Phys. Rev. Lett. 66, 1938 (1991)]

When $l_\phi < R$

$$T_\sigma(\omega) = -\Gamma_1 \Im G^0_{11}(\omega) - \Gamma_2 \Im G^0_{22}(\omega) + 2\Gamma_1\Gamma_2[\cos(\Phi_\sigma)\Re G^0_{11}(\omega)\Re G^0_{22}(\omega) - \Im G^0_{11}(\omega)\Im G^0_{22}(\omega)]$$

$$G^0{}_{22}(\omega) = [\omega - \epsilon_j + i\Gamma_j]^{-1}$$

$$G_{11\sigma}{}^0(\omega) \rightarrow G^r_{11\sigma}(\omega) = \frac{1 - \langle n_{\bar\sigma}\rangle - X^r_{\bar\sigma}(\omega)}{\omega - \epsilon_1 + i\Gamma_1 - \cancel{\Sigma^r_{2\sigma}}(\omega)[X^r_{\bar\sigma}(\omega) - 1] - Y^r_{\bar\sigma}(\omega) - i\Gamma_1 X^r_{\bar\sigma}(\omega)}$$

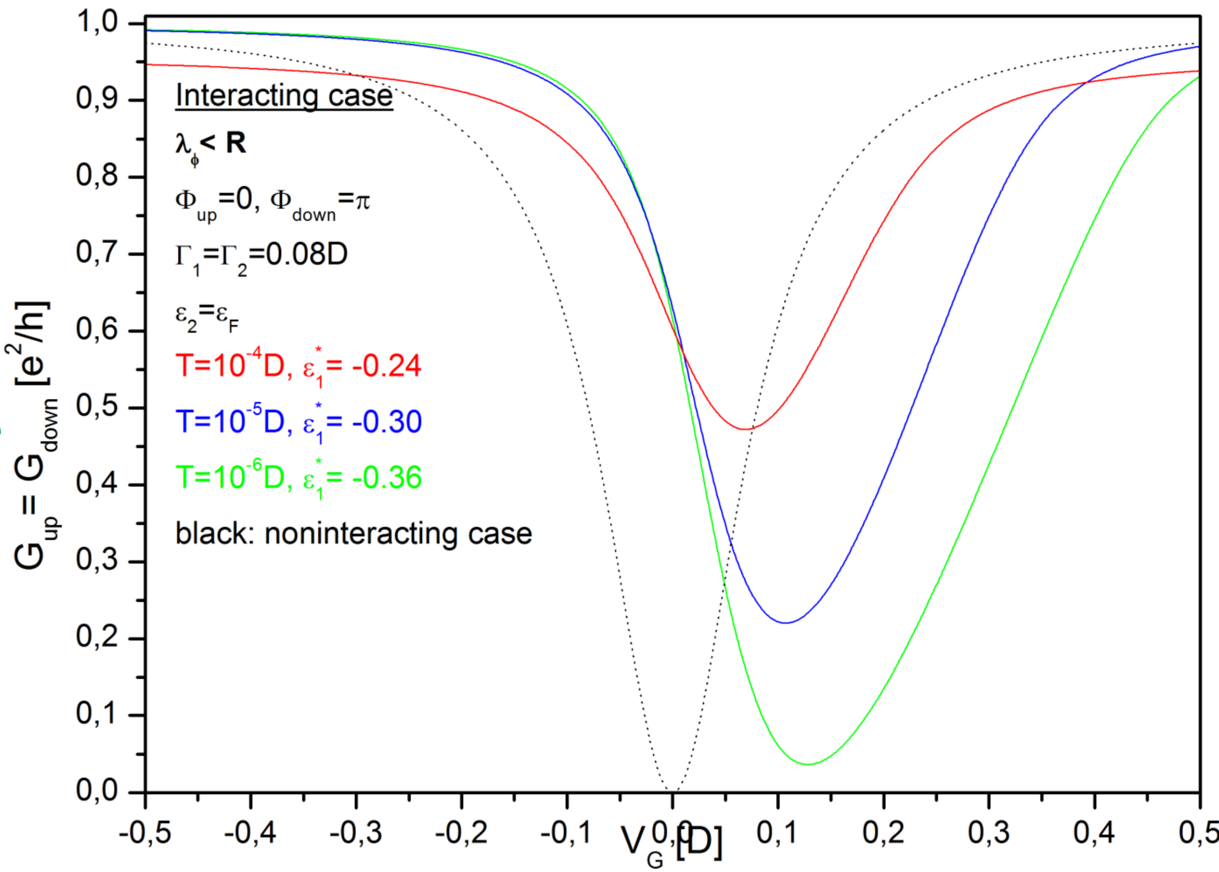
$$T_{\Phi=0/\pi}(\epsilon_F) = \frac{\Gamma_2{}^2}{\epsilon_2{}^2 + \Gamma_2{}^2}\frac{(\tilde\epsilon_1{}^2 \pm q)^2}{\tilde\epsilon_1{}^2 + 1}, \qquad \tilde\epsilon_1 = \frac{\epsilon_F - \epsilon_1}{\Gamma_1}, q = \frac{\epsilon_F - \epsilon_2}{\Gamma_2}, \quad \epsilon_1 \rightarrow \epsilon_K$$

Fano-Kondo resonance

For effective phases

$\Phi_{\uparrow} = 0$ i $\Phi_{\downarrow} = \pi$

- No spin polarization
- the minimum of Fano resonance deepens with *decrease* of temperature



$$V_G = -\epsilon_1{}^*$$

$$T_{\uparrow}(\epsilon_F) = T_{\downarrow}(\epsilon_F) = 1 + \Gamma_1 \Im G^0_{11}(\epsilon_F)$$

Conclusions:

- combined action of Aharonov-Bohm and Rashba fields can produce spin-dependent pseudo-gap in the investigated system

- spin polarization at Fermi energy is generated by spin selective diminishing of strong electron correlations on the Kondo QD level

- appearance of the „dark states” in a parallel DQD system as result of QD level coupling to the host with pseudogap

- spin polarization of zero-bias conductance depends crucially on the phase coherence length (activation or not spin dependent pseudogap) and has unusual temperature dependence for $l_{\phi} > R$

Thank you for your attention !